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ORIGINAL ARTICLE

Pre-Aksumite and Aksumite Agricultural Economy at Ona Adi, Tigrai (Ethiopia): First look at a 1000-Year History

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Abstract Archaeobotanical investigations at the site of Ona Adi in Tigrai were conducted during the 2013–2015 field seasons within the framework of the Eastern Tigrai Archaeological Project (ETAP). The site occupation spanned the Middle/Late Pre-Aksumite period (ca. 750/600 BCE) to the fall of the Aksumite Kingdom (ca. 700 CE), including the Pre-Aksumite to Aksumite transition (ca. 400 BCE–CE 1). The main objective of the study was to examine the agricultural economy in Eastern Tigrai during these periods and to evaluate the impact of social and cultural developments on the agricultural practices at Ona Adi. Recovered macrobotanical remains included wheat, barley, linseed, noog, lentil, and wild/weedy plants. In addition, evidence of finger millet was recovered along with tentative identifications of t'ef. The phytolith record shows evidence of grass processing, including morphotypes associated with Chloridoideae, Panicoideae, and Pooideae grasses. Results indicate that plants of both African and Southwest Asian origins were present in the region from the mid-eighth century BCE to the eighth century CE, but their relative importance varied throughout time in relation to socio-political changes at the regional level. Our data demonstrate a significant degree of continuity in the local agricultural economy, which remained largely unchanged even after the decline of Aksumite state.

Résumé Les investigations archéobotaniques menées sur le site d'Ona Adi en Tigrai ont été réalisées au cours des 2013-15 dans le cadre du projet Eastern Tigrai Archaeological Project (ETAP). L'occupation du site s'étend de la période pré-axoumite moyenne/tardive (env. 750/600 av. J.-C.) à la chute du royaume axoumite (env. 700 ap. J.-C.), incluant la transition de la période pré-axoumite à axoumite (env. 400 av. J.-C.—1 ap. J.-C.). L'objectif principal de l'étude était d'examiner l'économie agricole dans l'Est de Tigrai pendant ces périodes et d'évaluer l'impact des dével-

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oppements sociaux et culturels sur les pratiques agricoles à Ona Adi. Les restes macrobotaniques récupérés comprenaient du blé, de l'orge, du lin, du noog, de la lentille et des plantes sauvages/indésirables. De plus, des preuves de millet à doigt ont été retrouvées, ainsi que des identifications provisoires de t'ef. L'enregistrement des phytolithes montre des preuves de traitement des herbes, y compris des morphotypes associés aux herbes des sous-familles Chloridoideae, Panicoideae et Pooideae. Les résultats indiquent que des plantes d'origine africaine et d'Asie du Sud-Ouest étaient présentes dans la région du milieu du VIIIe siècle av. J.-C. au VIIIe siècle ap. J.-C., mais leur importance relative variait en fonction des changements socio-politiques au niveau régional. Nos données démontrent un degré significatif de continuité dans l'économie agricole locale, qui est restée largement inchangée même après le déclin de l'État axoumite."

Keywords Archaeobotany · Early agriculture · Rise of state · Pre-Aksumite period · Kingdom of Aksum · Horn of Africa

Mots-clés **archéobotanique** · agriculture ancienne · montée de l'État · période pré-axoumite · Royaume d'Aksum · Corne de l'Afrique."

Introduction

The northern Horn of Africa is an important center of diversity for a range of economically important species such as t'ef (*Eragrostis* (Zucc.) Trotter), barley (*Hordeum vulgare* L.), and sorghum (*Sorghum bicolor* (L.) Moench), among others (Barnett, 1996; Beldados et al., 2023; Brandt, 1984; Curtis, 2013; Ehret, 1979; Harlan, 1969, 1971; Harrower et al., 2010; Marshall & Hildebrand, 2002; Ruiz-Giralt et al., 2023a; Vavilov, 1951), whereas the history of Southwest Asian crops such as wheat (*Triticum* L. sp.), barley, linseed (*Linum usitatissimum* L.), and lentil (*Lens culinaris* Medik.) are well documented in the region (Beldados et al., 2023; Boardman, 2000; D'Andrea, 2008; D'Andrea et al., 2008a), the archaeological evidence of indigenous plants has been minimal). Indeed, there has been a clear underrepresentation of indigenous African crops compared to Southwest Asian species in archaeological samples, and the systematic use of local species has only been brought to light by recent studies (Beldados et al., 2023; Ruiz-Giralt et al., 2023a). In this regard, progress in archaeobotanical studies in the highlands of the northern Horn of Africa has been slow but steady. Initial macrobotanical studies were completed at the D- and K-sites (Boardman, 1999, 2000), as well as at Ona Nagast (D'Andrea, 2008), both near Aksum (Tigrai, Ethiopia) (Fig. 1). Further macrobotanical studies were carried out at a number of Ancient Ona sites in the Asmara region of Eritrea (D'Andrea et al., 2008a) and at the Pre-Aksumite site of Mezber (Tigrai, Ethiopia) (Beldados et al., 2023). At Mezber, microbotanical analyses were initiated by D'Andrea et al. (2018) and continued by Ruiz-Giralt et al. (2023a). As a result, it is currently understood that agricultural practices began in the Ethiopian highlands at least by the mid-2nd millennium BCE, with early plant cultivation centered on barley, linseed, lentil, and probably indigenous wild grasses (Beldados et al., 2023; D'Andrea et al., 2023; Ruiz-Giralt et al., 2023a). According to the published evidence (summarised in Table 1), the spread of sedentary settlements throughout the highlands during the early 1st millennium BCE came with the cultivation of new crops, including emmer (*Triticum dicoccum* Schrank ex Schübl.), free-threshing wheat (*T. durum* Desf./*T. aestivum* L.), t'ef, and possibly noog (*Guizotia abyssinica* Cass.) (Boardman, 2000; D'Andrea, 2008; D'Andrea et al., 2008a; Meresa, 2017). With the rise of the Aksumite Kingdom after the first century CE, sorghum, and finger millet (*Eleusine coracana* Gaertn.), along with a range of pulses, tuberous plants, and other economic crops were added to the highland agricultural complex (Boardman, 2000; D'Andrea, 2008; Ruiz-Giralt et al., 2023a).

Despite the limited number of studies, it is believed that it was during the Pre-Aksumite and Aksumite periods when food producing, socially complex polities were present in the northern Horn of Africa. Most hypotheses developed so far to explain these cultural developments have been based on research focused on Central/Western Tigrai, in the regional centers of Yeha and Aksum (Anfray, 1972a, 1972b; Bard et al., 1997, 2014; Chittick, 1974; Fattovich & Bard, 2001; Michels, 1994, 2005; Munro-Hay, 1989; Negash, 1997). On the contrary, other regions such as Eastern Tigrai have only been systematically surveyed in the last decade (Benoist et al., 2020; D'Andrea et al., 2008b; Dugast & Gajda, 2014;

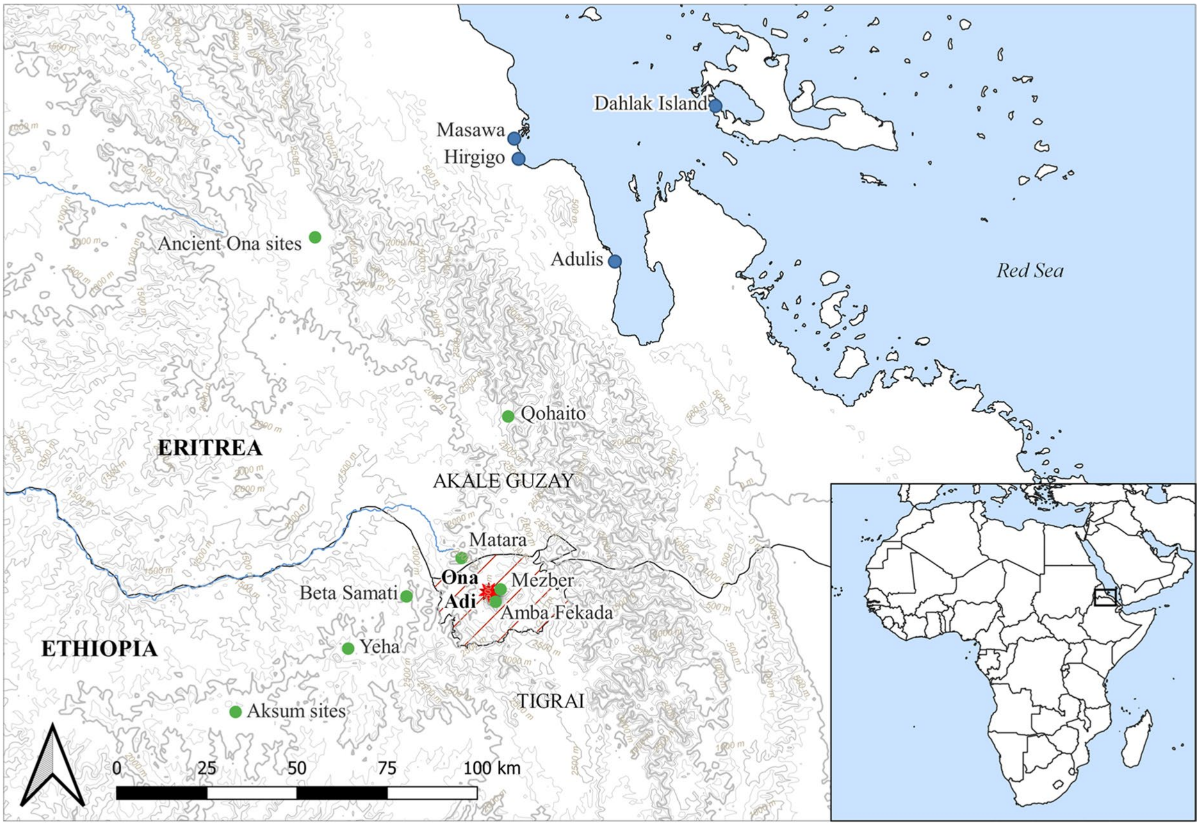

Fig. 1 Map of the northern Horn showing significant locations mentioned in the paper: green dots are sites, blue dots are port sites, and the red star represents Ona Adi. The shaded area is Gulo Makeda district

Table 1 Summary of published archaeobotanical literature to date

Site name	Identified taxa	Dates
Mezber (Beldados et al., 2015, 2023; D'Andrea et al., 2023; Ruiz-Giralt et al., 2023a, 2023b)	Barley, lentil, linseed, Chloridoideae, Panicoideae, underground storage organs (USO), emmer (ca. 850 BCE), cf. t'ef (ca. 400 BCE)	ca.1600 BCE-25 CE
Ancient Ona sites, including Sembel, Mai Chiot, Weki Duba, Mai Hutsa, Ona Gudo (D'Andrea et al., 2008a)	Barley, lentil, linseed, emmer, free threshing wheat (Sembel, ca. 800 BCE), t'ef (Mai Chiot, ca. 400 BCE)	ca. 800–300 BCE
D-site, Aksum, Pre-Aksumite occupation (Boardman, 2000)	Barley, lentil, linseed, emmer	ca. 800–400 BCE
Beta Samati (Harrower et al., 2019)	Emmer	ca. 800 BCE-800 CE
Ona Nagast, Aksum (D'Andrea, 2008)	Barley, lentil, linseed, emmer, free-threshing wheat, possible t'ef, finger millet (ca. 50 CE), grape (ca. 50 CE)	ca. 400 BCE-700 CE
D- and K-sites, Aksum, Aksumite occupation (Boardman, 2000)	Barley, lentil, linseed, emmer, free-threshing wheat, t'ef, finger millet, sorghum (only at D-site), oat, chickpea, grass pea, pea, faba bean, noog, cotton, cress and grape	ca. 500–700 CE
Tomb of the Brick Arches, Aksum (Boardman, 2000)	Sorghum	ca. 200–550 CE

Gajda et al., 2020; Harrower & D'Andrea, 2014; Harrower et al., 2022; Wiederick, 2020; Wolf and Nowotnick 2010) despite being known to contain significant archaeological sites (Anfray, 1973). The Eastern Tigrai Archaeological Project (ETAP) has engaged in archaeological surveys, excavations and ethnoarchaeological research since 2004, focusing on the district of Gulo Makeda, located 15 km north of the city of Adigrat. ETAP objectives have included the investigation of early social complexity and elucidation of the agricultural history of the highlands. Over the last few years, a number of research results related to the project objectives have been published in theses and articles (Beldados et al., 2015, 2023; Biagetti et al., 2022; D'Andrea et al., 2008b, 2011a, 2011b; 2018; 2023; Harrower & D'Andrea, 2014; Mekonnen, 2019; Meresa, 2017; Nixon-Darcus, 2014, 2022; Nixon-Darcus & D'Andrea, 2017; Nixon-Darcus & Meresa, 2020; Peterson, 2017; Ruiz-Giralt et al., 2021, 2023a, 2023b; Walder-Hoge, 2018; Wiederick, 2020; Woldekiros & D'Andrea, 2017, 2022; Woldekiros et al., 2019).

The present article focuses specifically on Pre-Aksumite and Aksumite archaeobotanical remains recovered from the urban site of Ona Adi, and it has two objectives: (1) determination of economically useful plants during the Late Pre-Aksumite, Pre-Aksumite to Aksumite transition (PA-A transition), and Aksumite periods in Gulo Makeda; and (2) investigation of whether social and cultural changes involved in the rise and decline of the Kingdom of Aksum had a significant impact on the agricultural economy of the region.

The Study Area: Gulo Makeda in Eastern Tigrai

The total area of Gulo Makeda *woreda* (administrative district) is ca. 630 square kilometers. It borders the historic provinces of Akale Guzay (Eritrea) to the north, the Tigrayan province of Adwa to the west, Temben and Enderta (Tigrai) to the south and both the Ethiopian and Eritrean Afar lowlands to the east (Fig. 1). Topographically, the area exhibits diverse physical features including mountains, plateaus, deep gorges, and river valleys. The elevation of Eastern Tigrai ranges from 2100 to over 3000 m above sea level (masl), to include some of the highest mountains in Ethiopia, such as Mount Alequa (3291 masl) and Asimba (3248 masl) (Wilson & Pavlish, 2005). This topography provided suitable locations for defendable settlements at the top of the steep slopes, but they also made interregional connections and communications difficult in the past, resulting in a fragmentation of the population into isolated communities and distinct cultural traditions (Bard et al., 2000; Fattovich, 2012). Gulo Makeda has two drainage systems: first, watercourses which flow northwest to join the Mereb River and its tributaries; and secondly, rivers that flow eastward as seasonal tributaries into the Afar depression after joining Endale River. The highlands of Gulo Makeda form the watershed for both the north-western and eastern drainage systems (Meresa, 2017).

According to agroclimatic classifications, Gulo Makeda falls into *dega* (temperate belt, ca. 2400–3500 masl) and *woina-dega* (warm belt, ca. 1500–2300 masl) belts which are two of four agro-ecological zones based on altitude and described for Ethiopia (Getahun, 1984). The site of Ona Adi and the upper slopes of the escarpment and plateaus of Eastern Tigrai are situated in *woina-dega*, a temperate ecological zone. The high mountain tops, often covered with clouds, and their associated plateaus lie within *dega*, with average annual temperatures of 15 to 25 °C. Ethiopia experiences two rainy seasons: *kremt* (May to September) is the main season along with the shorter *belg* (February to April). Gulo Makeda receives relatively high amounts of *kremt* rain from June to August, with a mean annual rainfall range from 500 to 1000 mm. However, Tigrai has not experienced consistent *belg* rains for more than five decades. In fact, the region has been affected by droughts for millennia (Marshall et al., 2009, 2011; Nyssen et al., 2004). As a result, farmers who cannot rely on abundant rainfall have developed adaptations to unpredictable rainfall by growing several landraces to maintain high genetic diversity and planting drought resistant crops (Biagetti et al., 2022; Butler & D'Andrea, 2000). The agro-ecological landscape of this area is characterised by narrow fertile arable fields on river margins and other plains, disconnected by numerous seasonal streams and uneven physical locations dominated by small rolling and interrupted hills and hanging boulders (Meresa, 2017). Mixed farming is the dominant subsistence practice which accounts for about 82% of the total agricultural system: *dega* and *woina-dega* sectors are preferred for cultivation of sorghum, t'ef, wheat, barley, and finger millet, which are the most common cereal crops in the area today (CSA 2022), along with other agricultural products such as chickpea (*Cicer arietinum* L.), lentil (*Lens culinaris* Medik.), grass pea (*Lathyrus sativus* L), and linseed/flax (*Linum usitatissimum* L.).

Gulo Makeda has a continuous history of occupation from the LSA (Later Stone Age) to Post-Aksumite times, with the presence of Middle Stone Age (MSA) and possibly Early Stone Age (ESA) lithics recovered during ETAP surveys (D'Andrea et al., 2008b; Harrower & D'Andrea, 2014; Wiederick, 2020). The region was part of Pre-Aksumite and Aksumite polities, as demonstrated by the presence of many archaeological sites, including the well-known rock paintings of Amba Fekada (Graziosi, 1941; Meresa, 2006; Mordini, 1941) and the Pre-Aksumite site of Mezber, where an early occupation of the region by agro-pastoralist groups has been documented, ca. 1600 BCE (D'Andrea et al., 2023). Preserved pillars and other architectural features indicate that several towns were established in Gulo Makeda during Pre-Aksumite and Aksumite times (Anfray, 1973), and numerous archaeological sites have been investigated (Anfray, 1965, 1973, 1974; Caquot & Drewes, 1955; Coulbeaux, 1929; D'Andrea et al., 2008b; Franchini, 1953; Harrower & D'Andrea, 2014; Leclant & Andre, 1959; Mordini, 1941; Rossini, 1928). Although more numerous than sites in Central/Western Tigrai, ETAP sites tend to be smaller in size (Harrower & D'Andrea, 2014), with a lack of large urban centers in favor of mid-size regional towns participating in the movement of people and goods from the Red Sea region to Aksum (Cerulli, 1960; D'Andrea et al., 2008b; Manzo, 1998). As part of the eastern territory of the Aksumite Kingdom, the importance of Gulo Makeda essentially derived from its strategic location on ancient trade routes connecting the vital Red Sea entrepots of Hirgigo, Masawa, Dahlak Island, and Adulis with the rich highland interior of northern and central Ethiopia (Cerulli, 1960; Manzo, 1998). Major trade and caravan routes crossed the Gulo Makeda area and included those running from the Danakil Desert to the interior plateau of Akele Guzai to Tigrai, from Aksum and Yeha via Matara and Qohaito to the Gulf of Zula. Commodities moving through the region included ivory, incense, rhinoceros' horn, salt, tortoise shell, and obsidian (Fattovich, 1999; Munro-Hay, 1991; Phillipson, 1998, 2012; Raunig, 2004; Woldekiros, 2023), demonstrating the economic importance of the region.

Over the past 15 years, ETAP has documented over 162 sites within a 296 square kilometers area dating from the Middle Stone Age to Post Aksumite periods. Out of this total, 37 correspond to Pre-Aksumite and 80 to Aksumite settlement sites (D'Andrea et al., 2008b; Harrower & D'Andrea, 2014; Wiederick, 2020). It is worth noting that some Pre-Aksumite settlements were later occupied during Aksumite times (D'Andrea et al., 2008b; Wiederick, 2020), usually increasing in size (Harrower & D'Andrea, 2014). Recent analysis of site size hierarchies and spatial clustering have shown that some of these sites, including Ona Adi, became major settlement nodes articulating a densely occupied area because of a significant increase in population that was maintained until the eighth century CE (Harrower & D'Andrea, 2014; Harrower et al., 2022). According to Harrower et al. (2019), these sites acted as regional centers of administration, whereas Benoist et al. (2021) have argued that they served as outposts. In any case, the Aksumite occupation of Gulo Makeda was not only determined by demographic growth, but also by landforms and water-rich areas which were preferentially occupied due to their high agricultural potential (Harrower & D'Andrea, 2014).

Case Study: Ona Adi

The site of Ona Adi is situated close to the modern villages of Menebeity and Etchmare, in Tabia Shewit Lemlem, at an altitude of 2452 masl. The site covers 9.74 hectares and is characterised by buried and exposed ancient wall ruins, an ancient crypt under the church of Enda Petros, and a large area of agricultural land showing high concentrations of stone architectural debris and ceramics. The site was excavated in seven fields (A–F) some of which were subdivided into squares (D1, 2) (Fig. 2). Excavation proceeded using loci, which were natural or anthropogenic depositional units, or as arbitrary 10-cm levels when stratigraphic layers were large or not easily distinguished. Loci were further sub-divided into pails which were artificial or natural sedimentary sub-units within loci. All flotation samples recovered from sedimentary loci were assigned unique serial numbers. The pottery recovered from the site revealed five phases

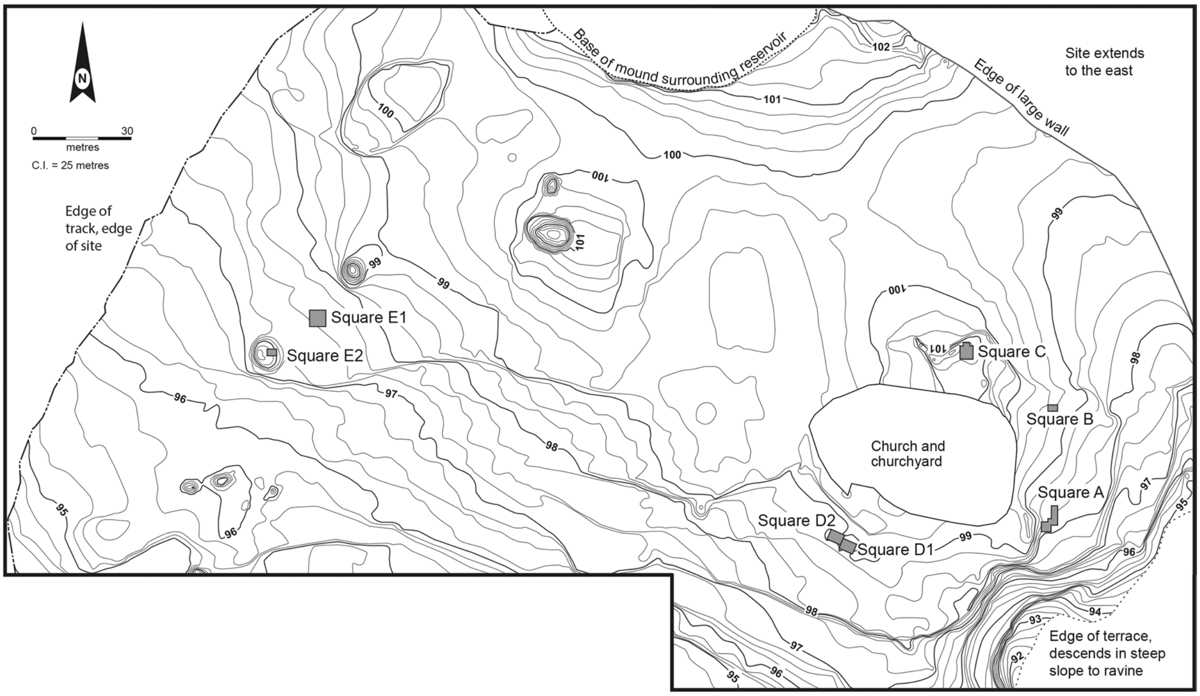

Fig. 2 Excavations at Ona Adi (map by Shannon Wood)

of occupation, spanning ca. 1500 years (Mekonnen, 2019: 339): (1) Middle/Late Pre-Aksumite (ca. 750/600–400 BCE), (2) Pre-Aksumite to Aksumite (PA-A) transition (400 BCE–CE 1), (3) Early Aksumite (ca. CE 1–330), (4) Middle Aksumite (ca. CE 330–500) and Late Aksumite (ca. CE 500–700). Ona Adi is among the numerous sites known to have been inhabited during the PA-A transition in Gulo Makeda. This period was marked by the abandonment of settlements around the regional centers of Yeha and Aksum (D'Andrea et al., 2008b; Mekonnen, 2019). In this regard, it has been posited that populations from nearby sites such as Mezber might have relocated to Ona Adi, an Aksumite urban site featuring monumental buildings and ceremonial pottery that points to the presence of elite groups. The discovery of two coins depicting Aksumite kings suggest that the leadership of the Aksumite heterarchical polities might have been present at Ona Adi (Harrower et al., 2022). Further, the pottery, lithics and grinding stones recovered during ETAP investigations indicate that past artisans had significantly refined their craftsmanship skills, demonstrating advanced technical knowledge (Mekonnen, 2019; Nixon-Darcus, 2022; Peterson, 2017).

Materials and Methods[1]

Carpology

Ona Adi macrobotanical sampling initially prioritised Field D, including Squares D1 and D2, because they revealed Pre-Aksumite deposits superimposed by Aksumite period remains. These units therefore had the potential to provide data on the full occupation of the site, including the PA-A transition (Meresa, 2017). Additional sampling took place in Squares A1,

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[1] The Tigrai civil war halted all research in the study region between November 2020 and January 2023. It resulted in the looting and destruction of ETAP archaeological collections and storage facilities in Adigrat. It also decimated Aksum University infrastructure, including material collections and computers where most of the original materials presented in this paper were stored. This precluded our ability to revisit collections for imaging and other purposes.

B1, C1, E1 and E2. A total of 76 bulk soil samples from a variety of contexts were recovered for flotation (Table 2, raw data including mixed and non-productive context is available as Supplementary Materials 1). A re-circulating bucket flotation system was used to capture floating charred remains. All water was changed, and equipment thoroughly cleaned every six samples or when deemed necessary. Screens of both 1 mm and 0.25-mm mesh sizes were used to separate heavy and light fractions samples, which were subsequently dried, bagged and labelled for later analysis. Outflow passed through a 0.02-mm mesh and settled in a tank at least overnight before being reused (Beldados et al., 2023).

The laboratory work involved sorting charred grains using a binocular microscope (10–40×). Macrobotanical remains were identified as closely as possible to the species level using comparative collections held in the Archaeology Laboratory at Addis Ababa University and ETAP storerooms in Adigrat. Digital images of the recovered macrobotanical remains were captured using a Dino-Lite Premier Digital Microscope AM41131. Ona Adi light fractions produced large quantities of charred botanical remains. Heavy fractions were scanned by laboratory assistants and found not to contain large quantities of macrobotanical remains. As such, this discussion focuses on the light fractions Fig. 3.

Phytolith

A total of 47 phytolith samples from Ona Adi were analyzed. Samples were selected according to stratigraphical criteria to cover the entire occupational sequence of the site, and they included samples from fill ($n=30$), living floors ($n=7$), middens ($n=5$), and ash accumulations ($n=5$). The extraction of phytoliths was performed using the protocol described by Madella et al. (1998) but adapted to reduce the effect of highly concentrated chemicals during long periods of exposure (for example, the concentration of hydrochloric acid reduced to 5%, see Cabanes et al., 2011), and to calculate the Acid-Insoluble Fraction (AIF) following Albert and Weiner (2001). Following Lombardo et al. (2016), sonication was introduced during the removal of soil organic matter (with hydrogen peroxide) and clay (with sodium hexametaphosphate) to facilitate their separation from the mineral fraction. Phytolith slides were prepared with a permanent medium (Entellan®), and they were analyzed and photographed using a Euromex iScope microscope at × 400 magnification with an Euromex scientific camera sCMEX-6.

A minimum of 250 single cell phytoliths were identified in each sample and multicell phytoliths (silica skeletons) were counted separately (Fig. 4). Correlation between phytolith concentration and number of morphotypes identified was evaluated using Pearson's coefficient to assess the impact of taphonomic processes on the phytolith assemblages (Madella & Lancelotti, 2012). The Kruskal–Wallis H test was used to compare sample phytolith composition between phases and types of contexts. Due to the extensive breakage of silica skeletons and the generally low number of cells per skeleton, preventing the measurement of crucial features, morphometric analyses were not completed (cf. Ball et al., 2016; Lu et al., 2009; Rosen, 1992; Zhang et al., 2011, 2018).

Phytoliths were described according to the International Code for Phytolith Nomenclature (ICPN) 2.0 (Neumann et al., 2019) and taxonomical and anatomical interpretations followed Ruiz-Giralt et al., (2023a, Supplementary Materials, pp. 52–114, available at https://zenodo.org/record/7731566). A synthesis can be found in the Supplementary Materials 2 of this article. In addition, a methodological note is needed regarding the taxonomical interpretation of silica skeletons containing ELONGATES DENDRITIC with PAPILLATE (Fig. 4c). In the present work, they were considered to be diagnostic of Poaceae cf. Pooideae cereals. Indeed, elongate dendritic phytoliths are known to be produced in abundance by domesticated grass species within the Triticeae and Poeae tribes (subfamily Pooideae) (Neumann et al., 2019). As such, the presence of this morphotype in African agropastoral sites has been commonly interpreted as evidence of domesticated Southwest Asian cereals such as wheat and barley (e.g., Lancelotti et al., 2021; Madella et al., 2014; Out et al., 2016; Portillo et al., 2012). Recent studies have challenged the traditional association between dendritic phytoliths and domesticated Pooideae cereals. Novello and Barboni (2015) report the presence of "Dendritic elongate phytoliths (type El3d)" in a number of wild African species from other subfamilies including *Eragrostis squamata* (Lam.) Steud. (Chloridoideae), *Oryza longistaminata* A.Chev. & Roehr (Ehrhartoideae), *Andropogon pseudapricus*

Table 2 Macrobotanical remains identified at Ona Adi. *PA* Pre-Aksumite, *A* Aksumite, *PA-A T* Pre-Aksumite to Aksumite transition

Field	Square	Locus	Pail	Period	*Triticum* sp.	*Hordeum vulgare*	*Eleusine coracana*	*Eragrostis* cf. *tef*	*Linum usitatissimum*	*Guizotia abyssinica*	*Lens culinaris*	*Lolium* sp.	*Galium spurium*	Chenopodium cf. *album*	*Rumex* cf. *crispus*	Unidentified	Total
D	1	15	29	Late PA	6	0	0	0	0	0	0	0	0	0	0	0	6
D	1	16	30	Late PA	0	0	0	0	0	0	0	3	0	1	0	0	4
D	2	26	57	Late PA	12	3	0	0	0	0	0	5	0	6	0	0	26
D	2	26	57	Late PA	9	0	0	0	0	0	0	7	8	0	0	0	24
Total late PA					**27**	**3**	**0**	**0**	**0**	**0**	**0**	**15**	**8**	**7**	**0**	**0**	**60**
D	1	13	23	PA-A T	0	0	0	0	0	0	0	0	0	3	0	0	3
D	1	14	24	PA-A T	12	0	0	0	0	0	0	0	0	4	0	0	16
D	2	25	56	PA-A T	3	2	0	0	0	0	0	0	0	5	0	0	10
D	2	25	56	PA-A T	2	5	0	0	0	0	0	0	0	13	11	0	31
D	2	25	56	PA-A T	0	0	0	0	0	0	0	0	0	6	0	0	6
D	2	25	56	PA-A T	2	3	0	0	0	0	0	0	0	7	9	0	21
D	2	25	56	PA-A T	3	7	0	0	57	5	20	0	0	0	0	100	192
Total PA-A T					**22**	**17**	**0**	**0**	**57**	**5**	**20**	**0**	**0**	**38**	**20**	**100**	**279**
C	1	18	68	Early A	0	1	0	0	0	0	0	2	0	0	0	0	3
C	1	19	74	Early A	0	0	0	0	0	1	0	1	0	1	0	0	3
D	1	9	15	Early A	5	0	0	0	1	0	0	3	0	0	0	0	9
D	1	10	17	Early A	7	0	0	0	2	0	0	2	0	0	0	0	11
D	1	10	18	Early A	0	0	0	0	0	0	0	6	0	0	0	0	6
D	2	13	19	Early A	1	0	0	0	0	0	0	0	0	0	0	7	8
D	2	14	28	Early A	7	23	0	7	18	0	6	0	0	0	0	33	94
D	2	14	35	Early A	1	0	0	0	0	0	0	0	1	3	0	0	5
D	2	21	52	Early A	7	0	0	0	0	0	0	9	11	0	0	0	27
Total early A					**28**	**24**	**0**	**7**	**21**	**1**	**6**	**23**	**12**	**4**	**0**	**40**	**166**
A	1	4	16	Middle A	7	0	0	0	2	0	0	0	0	0	0	0	9
B	1	11	24	Middle A	20	0	0	0	4	5	2	11	0	0	0	0	42
B	1	12	27	Middle A	3	0	0	0	0	0	0	4	3	0	0	0	10
B	1	12	27	Middle A	0	0	0	0	0	0	0	4	6	0	0	0	10
B	1	13	29	Middle A	3	0	0	0	0	0	0	3	0	6	0	0	12
B	1	13	31	Middle A	4	0	0	0	0	0	0	4	6	0	0	0	14
C	1	3	12	Middle A	5	0	0	0	0	0	0	7	7	0	0	0	19
C	1	18	69	Middle A	4	0	0	0	0	0	0	3	8	0	0	0	15
D	1	7	11	Middle A	4	0	0	0	0	0	2	0	0	0	0	0	6
D	1	7	12	Middle A	10	2	0	0	0	0	0	6	0	0	0	0	18
D	1	7	13	Middle A	0	0	0	0	0	0	2	2	0	0	0	0	4

Table 2 (continued)

Field	Square	Locus	Pail	Period	*Triticum* sp.	*Hordeum vulgare*	*Eleusine coracana*	*Eragrostis* cf. *tef*	*Linum usitatissimum*	*Guizotia abyssinica*	*Lens culinaris*	*Lolium* sp.	*Galium spurium*	Chenopodium cf. *album*	*Rumex* cf. *crispus*	Unidentified	Total
D	2	7	17	Middle A	3	0	0	0	0	0	0	0	0	0	0	0	3
D	2	8	25	Middle A	1	0	0	0	0	0	0	0	0	0	0	0	1
D	2	12	40	Middle A	160	6	0	0	9	0	0	0	0	33	0	0	208
E	2	8	10	Middle A	29	0	0	0	0	0	8	18	0	31	8	0	94
Total middle A					**253**	**8**	**0**	**0**	**15**	**5**	**14**	**62**	**30**	**70**	**8**	**0**	**465**
A	1	3	22	Late A	3	0	0	0	1	0	0	4	0	0	0	0	8
A	1	3	27	Late A	0	0	0	0	0	0	0	5	0	5	0	0	10
B	1	6	13	Late A	2	0	0	0	0	0	0	6	3	7	0	0	18
B	1	7	14	Late A	0	0	0	0	1	0	0	3	0	4	0	0	8
B	1	7	15	Late A	24	0	0	0	6	7	4	13	0	0	0	0	54
B	1	7	16	Late A	2	0	0	0	0	0	0	4	0	0	0	0	6
B	1	9	18	Late A	0	0	0	0	1	0	0	3	0	4	0	0	8
B	1	10	19	Late A	2	0	0	0	0	0	0	2	3	0	0	0	7
C	1	2	7	Late A	11	0	0	0	0	0	0	6	13	0	0	0	30
C	1	2	14	Late A	16	0	0	0	6	5	6	21	39	0	0	0	93
D	1	3	5	Late A	8	0	0	0	0	0	0	8	0	0	0	0	16
D	1	6	6	Late A	0	6	0	0	5	5	7	0	0	0	0	3	26
D	1	6	7	Late A	16	0	0	0	0	0	0	2	0	2	0	0	20
D	1	6	8	Late A	12	6	0	0	0	0	0	4	15	0	0	0	37
D	1	6	9	Late A	2	14	2	0	7	75	13	0	0	0	0	32	145
E	1	2	2	Late A	0	0	0	0	0	0	0	0	0	0	0	0	0
E	1	3	4	Late A	0	0	0	0	0	0	0	5	0	7	0	0	12
E	1	3	5	Late A	0	0	0	0	0	0	0	8	9	6	0	0	23
Total late A					**98**	**26**	**2**	**0**	**27**	**92**	**30**	**94**	**82**	**35**	0	**35**	521
B	1	4	12	Post A	0	0	0	0	0	0	0	4	6	0	0	0	10
E	1	5	8	Post A	4	0	0	0	2	1	4	6	0	5	0	0	22
E	1	5	8	Post A	6	0	0	0	0	0	0	5	0	0	0	0	11
E	1	5	8	Post A	0	0	0	0	0	0	0	0	0	0	0	0	0
Total post A					**10**	**0**	**0**	**0**	**2**	**1**	**4**	**15**	**6**	**5**	**0**	**0**	**43**
Total Ona Adi					**438**	**78**	**2**	**7**	**122**	**104**	**74**	**209**	**138**	**159**	**28**	**175**	**1534**

Stapf (Panicoideae), *Cymbopogon giganteus* Chiov. (Panicoideae), *Diheteropogon amplectens* (Nees) Clayton (Panicoideae), *Hyparrhenia bagirmica* Stapf (Panicoideae), *H. rufa* (Nees) Stapf (Panicoideae), *Sehima ischaemoides* Forssk. (Panicoideae), *Sorghastrum stipoides* Kunth) Nash (Panicoideae), *Sorghum purpureosericeum* (Hochst. ex A.Rich.) Schweinf. & Asch. (Panicoideae), *Loudetia annua* (Stapf) C.E.Hubb. (Panicoideae), *Echinochloa obtusiflora* Stapf (Panicoideae), *Echinochloa stagnina* (Retz.) P.Beauv. (Panicoideae), and *Panicum laetum* Kunth (Panicoideae). Indeed, the images provided by Novello and Barboni (2015, Plate I-C-El3d) show elongated phytoliths with branched lateral processes. However, these are significantly different in size and complexity from those identified in the inflorescence brackets of domesticated wheat and barley (see, for example, Neumann et al., 2019, Supplementary Materials 1: 13, Figs. 5O, 5P and 5R; Piperno, 2006: 209, Figs. 3.11b and 3.11c; Rosen, 1992: 137–138, Figs. 7.5b and 7.7), which show larger elongated phytoliths with more complex dendriform processes articulated with silicified papillae. At Ona Adi, silica skeletons containing ELONGATES DENDRITIC resembled those produced by domesticated Pooideae (see Fig. 4c). According to the ICPN 2.0 (Neumann et al., 2019), morphometric and/or wave pattern analyses are needed to securely identify dendritic silica skeletons as Pooideae (see Ball et al., 2016, 2017; Rosen, 1992). Since morphometric analyses could not be carried out at Ona Adi due to the state of preservation of the silica skeletons, but abundant macrobotanical evidence of wheat and barley has been documented in the site, we have considered articulated ELONGATES DENDRITIC with PAPILLATE to be associated with Poaceae cf. Pooideae.

Results

Carpology

A total of 2852 macrobotanical remains were identified at Ona Adi, including grains, seeds, and chaff elements. Table 2 summarizes the recovered botanical remains according to their chronological and spatial contexts. The recovered botanical assemblage included both 55.8% domesticated (*n* = 1592) and 38.0% wild/weedy (*n* = 1085) plant remains, and 6.1% carpological remains were not identifiable (*n* = 175). The domesticated taxa comprised *Triticum* sp. (*n* = 1043, 36.6%), *Hordeum* sp. (*n* = 89, 3.12%), *Linum usitatissimum* (*n* = 216, 7.6%), *Guizotia abyssinica* (*n* = 161, 5.6%), *Lens culinaris* (*n* = 74, 2.6%), *Eleusine coracana* (*n* = 2, 0.1%), and *Eragrostis* cf. *tef* (*n* = 7, 0.25%). Identifiable weeds were dominated by *Gallium spurium* (*n* = 426, 14.9%), followed by *Lolium* sp. (*n* = 317, 11.1%), *Chenopodium* cf. *album* (*n* = 301, 10.6%) and *Rumex* cf. *crispus* (*n* = 41).

Triticum L. sp.

A total of 1043 complete grains, grain fragments and chaff elements assigned to *Triticum* sp. were recovered from all phases at Ona Adi (Fig. 3a, b). This accounts for 43.3% of the total macrobotanical assemblage. The types of *Triticum* recovered include free-threshing/bread wheat (*T. durum* Desf./*T. aestivum* L.) and emmer (*Triticum dicoccon* Schrank ex Schübl.). It is worth noting that a significant increase in the presence of *Triticum* sp. remains was recorded during the Middle Aksumite phase at Ona Adi, where they represent 62.5% (*n* = 253) of the assemblage –that is, over 40% more than during the Early Aksumite occupation of the site (20.9%, *n* = 28) (Fig. 5). In the following Late Aksumite phase, wheat remains continued to be the most common macrobotanical (20.8%, *n* = 98) though showing a similar frequency as noog and *Lolium* sp. Previous identifications of emmer and free-threshing wheat in the region have been made at Ona Nagast (D'Andrea, 2008), D- and K-sites near Aksum (Boardman, 1999, 2000), Ancient Ona sites near Asmara (D'Andrea et al., 2008a), Beta Samati (Harrower et al., 2019) and Mezber (Beldados et al., 2015, 2023).

Wheat is an important staple crop in Ethiopia, where it is used to make a variety of traditional leavened and unleavened breads, including flatbreads such as *injera/taita*, *embasha* and *kitsa* (Lyons & D'Andrea, 2003). Most wheat agriculture takes place in highland environments with cool temperatures at elevations ranging between 1000 and 2500 masl (Gorfu & Ahmed, 2011). At present, a significant number of free-threshing wheat landraces are cultivated (see Bishaw et al., 2014; Nigus et al., 2022) on approximately 10.5% of the total agricultural land of Tigrai (CSA 2022). Emmer agriculture, by contrast, has been gradually reduced and it only represents around 1% of Tigrai's agricultural production (CSA 2016).

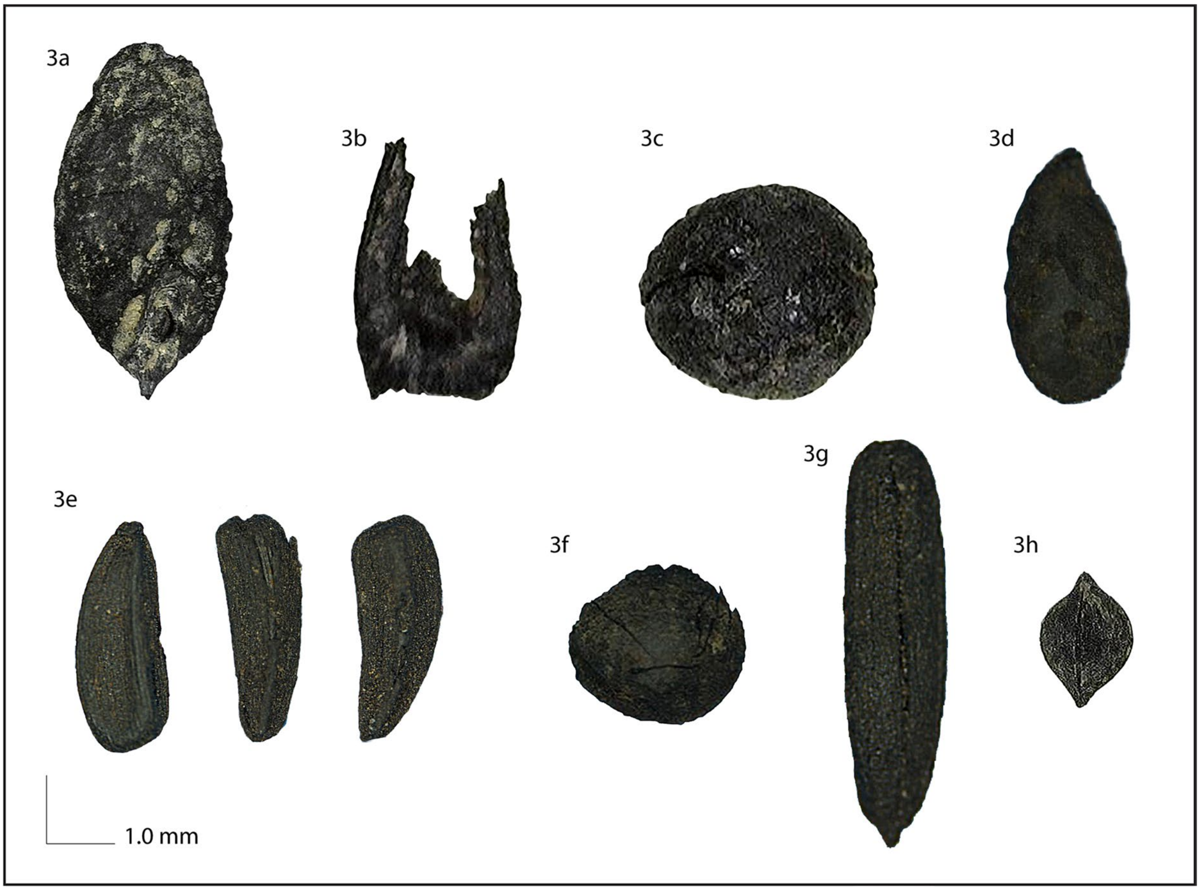

Fig. 3 Macrobotanical remains from Ona Adi: **a** *Triticum dicoccum* grain from Square A1, Locus 4, Pail 16, Serial #0276; **b** *Triticum dicoccum* spikelet fork from Square D2, Locus 25, Pail 56, Serial #1499; **c** grain of *Eleusine coracana* from Square D1, Locus 6, Pail 8, Serial #0734; **d** seed of *Linum usitatissimum* from Square D2, Locus 12, Pail 40, Serial #1420; **e** cypselae of *Guizotia abyssinica* from Square D2, Locus 25, Pail 56, Serial #1499; **f** *Lens culinaris* seed from Square D2, Locus 14, Pail 28, Serial #1337; **g** *Lolium* caryopsis from Square D2, Locus 26, Pail 57, Serial #1187; **h** *Rumex* cf. *crispus* from Square D2, Locus 25, Pail 56, Serial #1180

Hordeum vulgare L.

A total of 89 charred caryopses of *Hordeum vulgare* were recovered from Ona Adi contexts, accounting for 3.7% of the macrobotanical assemblage. Hulled barley appears consistently throughout all phases of the site occupation, although its importance appears to have diminished after the Early Aksumite phase, when it reached its highest values (17.9%, *n* = 24). During the following Middle Aksumite phase, the presence of barley was significantly reduced (2%, *n* = 8) mostly because of the increase in the relative frequency of wheat remains (Table 2). Previous reports of hulled barley in the region include Ona Nagast (D'Andrea, 2008), the D- and K-sites (Boardman, 1999, 2000), Ancient Ona sites (D'Andrea et al., 2008a), Beta Samati (Harrower et al., 2019) and Mezber (Beldados et al., 2015, 2023).

Barley is a key staple crop in many highland areas of Ethiopia, where it is cultivated without external inputs for the most part (e.g., fertilisers, herbicides). It thrives in the cool environments of highland areas, with an optimum altitudinal range between 2000 and 3500 masl (Gorfu & Ahmed, 2011). A number of important traditional food dishes are prepared using roasted barley flour (see D'Andrea et al., 2018; Mohammed et al., 2016; Shewayrga & Sopade, 2011). Barley is also used

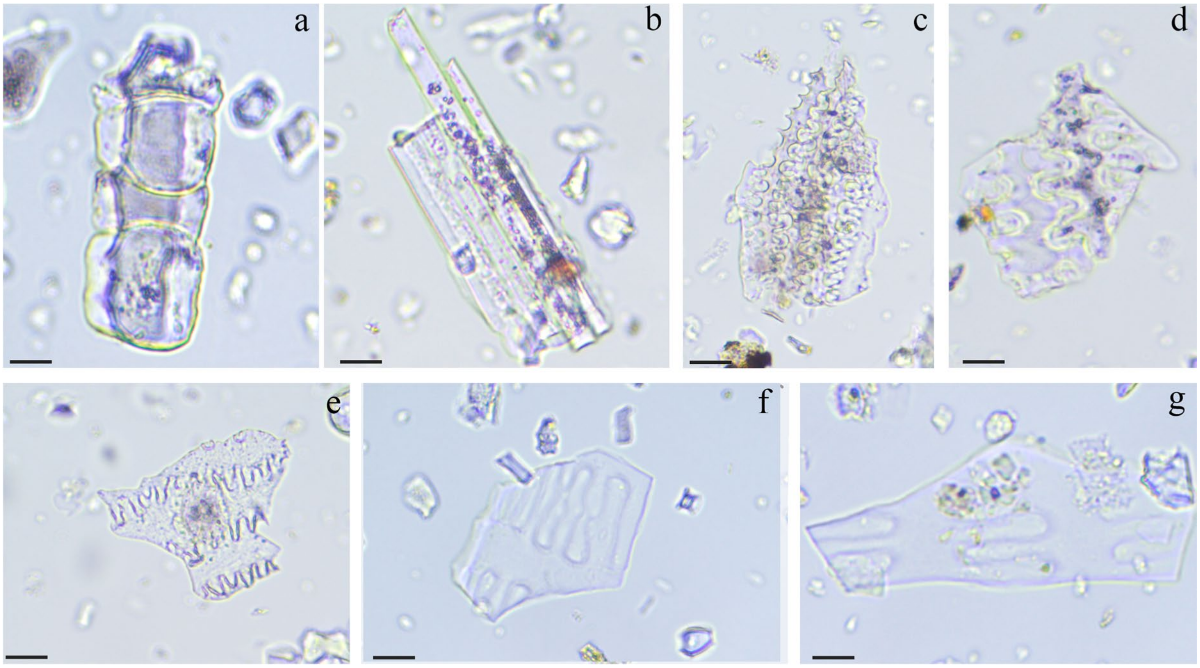

Fig. 4 Silica skeletons found at Ona Adi soil samples: **a** Articulated Bulliform (307-S1-F12-SK6), **b** Elongates entire (311-S1-F5-SK1), **c** Elongates dendritic (191-S1-F3-SK6), **d** Elongates sinuate wavy (125-S1-F10-SK10), **e** Elongates sinuate interdigitate Λ-shaped (1187-S1-F5-SK2), **f** Elongates sinuate interdigitate cf. β-shaped (2509-S1-F32-SK4), and **g** Elongates sinuate interdigitate Ω-shaped (2190-S1-F3-SK1). Scale bar is 10 μm

in the production of local beverages (Mohammad et al. 2016). While important in Eastern Tigrai, barley ranks as the fifth most important cereal crop in the country, behind sorghum, t'ef, wheat and finger millet. Barley agriculture comprises approximately 8.8% of the total area under cultivation in Tigrai (CSA 2022).

Eleusine coracana Gaertn.

Two grains of *Eleusine coracana* were identified from Square D1 (Fig. 3c). The sample is associated with Late Aksumite ceramics dating from the sixth to seventh/eighth century CE. Previous evidence in the region is very limited likely because of the limited preservation potential of finger millet macroremains, either as a result of taphonomic processes (see Young & Thompson, 1999) or in relation to its low survivability when exposed to heat (Mueller et al., 2022; Terefe & Beldados, 2021). D'Andrea (2008) recorded the oldest finger millet to date at Ona Nagast, where a single grain was identified in an Early Aksumite context (ca. 50 BCE–CE 150). The Post Aksumite occupation of Ona Nagast produced further evidence of finger millet (D'Andrea, 2008). Finger millet was also documented by Boardman (2000) at D- and K-sites, during the Late Aksumite occupation of Aksum, ca. 500- 700 CE.

Finger millet is consumed as a staple food only in a few areas of Tigrai, especially in the northern areas near the Eritrean border (Wilson, 2023). This cereal is very well adapted to the highlands, as it can grow in high altitude areas with low soil fertility and can withstand drought (Kumar et al., 2016; Maharajan et al., 2021). The ability of finger millet to grow in areas where other crops fail makes it a key crop for food security and human welfare. Indeed, its high calcium content makes it a crucial part of children's diet, and for pregnant and lactating women (Wilson, 2023). In addition, finger millet grains are malted and fermented to make traditional beer named *swa* (Biagetti et al., 2022). In 2019/2020, finger millet was the fourth most

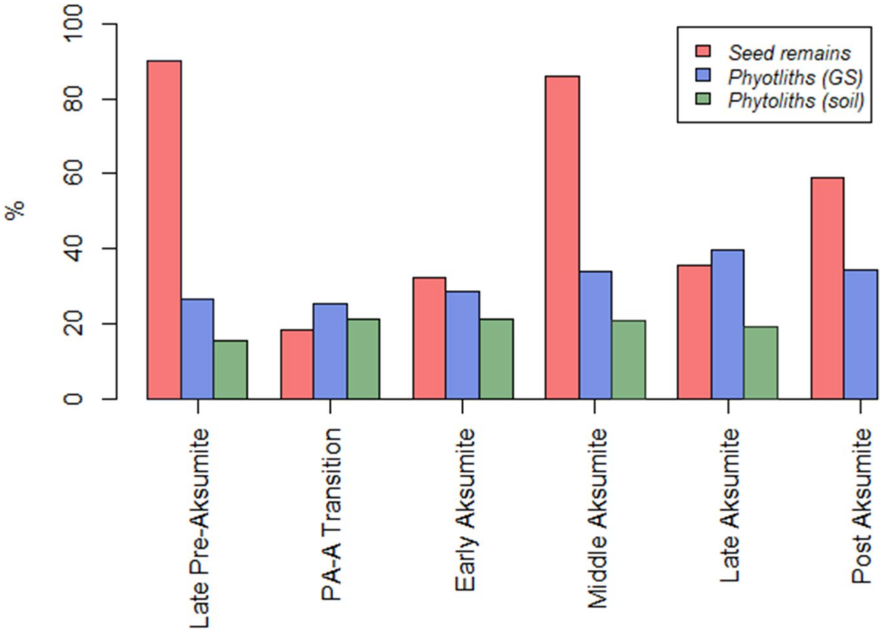

Fig. 5 Diachronic changes in the archaeobotanical evidence possibly associated with wheat at Ona Adi, including the evidence from the carpological remains (excluding wild plants and weeds) and soil phytoliths presented above, and the evidence from the grinding stone (GS) phytoliths presented by Ruiz-Giralt et al. (2023a)

cultivated crop in Tigrai, occupying around 9.4% of the cultivated land (CSA 2022).

Eragrostis cf. tef (Zucc.) Trotter

Seven grains identifiable to *Eragrostis* cf. *tef* were recovered from Square D2 Locus 14 Pail 28 Serial #1337, associated with Early Aksumite pottery and representing 0.3% of the macrobotanical assemblage. The length and width of these grains place them in an area of overlap between domesticated t'ef and wild *Eragrostis* sp. (D'Andrea, 2008). Evidence for the cultivation of t'ef has been recovered as early as the fourth century BCE at the site of Mai Chiot (D'Andrea et al., 2008a) and two grains were tentatively identified as t'ef at Mezber (Beldados et al., 2023). T'ef grains were also recovered from Aksumite deposits at several sites in Aksum (Boardman, 1999, 2000). These low quantities of t'ef grains may be the result of their inability to survive heating temperatures easily tolerated by larger cereal grains such as wheat and barley (D'Andrea, 2008).

T'ef is an indigenous small-grained cereal domesticated in the Ethiopian highlands where it is one of the most economically important cereal crops (D'Andrea, 2008). It is predominantly grown in the cool highland areas at an optimum altitude of 1800–2200 masl (Gorfu & Ahmed, 2011). In addition, t'ef can tolerate both extreme aridity and strong precipitation, and it is critical in enhancing food security in the region (Assefa et al., 2015). Until recently, t'ef agriculture occupied the main part of the land under cultivation in Tigrai (Gorfu & Ahmed, 2011) although it has been recently replaced by sorghum (CSA 2022). Still, it encompasses almost 20% of all land under cultivation in the region (CSA 2022). Regardless, t'ef continues to hold the highest social status and prestige value among all crops, as it provides the flour to make *injera*, a traditional pancake bread largely consumed throughout the country.

Linum usitatissimum L.

A total of 216 linseeds (or flax) were identified which comprise 9% of the total assemblage (Fig. 3d). With the exclusion of the recovered weeds from Ona Adi, it is the second most numerous charred seed identified from the site. Linseed appears for the first time at Ona Adi after the PA-A transition, when it represents 44.2% ($n = 57$) of the phase assemblage, and it is recorded consistently throughout the Aksumite and Post Aksumite occupation of the site although in much lower frequencies, ranging between 3.7 and 15.7%. Previous identifications of linseed in the region include the D- and K-sites (Boardman, 1999, 2000), Ona Nagast (D'Andrea, 2008), the Ancient

Ona sites (D'Andrea et al., 2008a), and Mezber (Beldados et al., 2015, 2023).

Linseed is an annual crop predominantly grown in temperate and cool tropical areas, including the highlands of the northern Horn of Africa (Amare & Abebe, 2022). In Ethiopia, linseed performs best in elevations ranging from 2200 to 2800 masl (Gudeta & Dechassa, 2017), where it is cultivated both as a fiber crop and as an oilseed (Amare & Abebe, 2022). Despite being the most ancient oil crop in the region known to date (Beldados et al., 2023; D'Andrea et al., 2023), today linseed agriculture only comprises about 1% of the agricultural land exclusively dedicated to oilseeds in Tigrai (CSA 2022). This is because linseed has been largely displaced by sesame (*Sesamum indicum* L.), which is cultivated on over 90% of the land dedicated to oilseeds, at about 11% of the total area under cultivation in Tigrai (CSA 2022). Still, linseed continues to be an important resource for small-landholder farmers, who commonly use it in crop rotation regimes (Biagetti et al., 2022). The seeds are generally used to make oil for household consumption, while the stem is converted to flax fibers. Linseed can also be roasted, ground into flour and mixed with spices to be eaten with *injera,* soups or as a constituent in porridges (Wilson, 2023).

Guizotia abyssinica Cass.

A total of 161 charred cypselae of noog (*Guizotia abyssinica*) were identified at Ona Adi, representing 6.7% of the macrobotanical assemblage (Fig. 3e). Identification of noog from archaeological contexts is rare (see Daniel & Beldados, 2018). At Ona Adi, it appears for the first time during the PA-A transition, although it is limited to a few remains until the Late Aksumite period, when it represents 19.6% ($n=92$) of the macrobotanical assemblage. There are also reports from the D- and K-sites in Aksum where it has been securely identified to the sixth to eighth century CE (Boardman, 2000).

Noog is a native oil crop to Ethiopia, where it was first domesticated at an unknown date (Fuller & Hildebrand, 2013). The main growing areas of this crop in Ethiopia are in the highlands between 1500 and 2500 masl, where it is cultivated mostly under rainfed conditions (Daniel & Beldados, 2018). In addition to its edible oil, noog is widely used in traditional Tigrayan cuisine (Geleta & Ortiz, 2013). The seeds can be grounded into flour to make condiments such as *chibto* (Daniel & Beldados, 2018). It is worth noting that although noog represents about 40% of all oilseeds consumed in Tigrai, its production is limited to less than 5% of the agricultural land dedicated to oilseed cultivation (CSA 2022), mostly because of the expansion of sesame as the main oil crop in the country (Wilson, 2023).

Lens culinaris Medik.

A total of 74 charred lentils (*Lens culinaris*) were recovered from Ona Adi deposits, comprising 3.1% of the assemblage total (Fig. 3f). Lentils were found in several contexts from the PA-A transition, where they represented 15.5% ($n=20$) of the sample. However, its presence was significantly reduced during the Aksumite occupation of the site, ranging between 3.5 and 6.4% during the Early, Middle, and Late Aksumite phases. A relative increase was recorded in the Post Aksumite phase, where they represented 9.5% ($n=30$) of the carpological record. Beyond Ona Adi, lentils have been recovered from a number of sites, including Ona Nagast (D'Andrea, 2008) and the D- and K-sites (Boardman, 1999, 2000), the Ancient Ona sites (D'Andrea et al., 2008a) and Mezber (Beldados et al., 2015, 2023).

Lentils are the earliest legumes known to be present in the northern Horn of Africa where they appear by approximately 900 BCE (Beldados et al., 2023). In Tigrai, they are mostly cultivated as winter crops, being sown immediately after the *kremt* rainy season when the soil is moist (Matny, 2015). This allows Tigrayan farmers to grow lentils in rotation with cereals due to its ability to fixate nitrogen in the soil, which significantly supports soil fertility (Wilson, 2023). This, along with the crop's resistance to drought, has made lentils a key agricultural product in the highlands of Tigrai, where it is cultivated on more than 15% of the agricultural land dedicated to legume agriculture (CSA 2022). As a protein-rich source of food, lentils are a key ingredient of local cuisine of Tigrai: seeds are grounded and used in soups and local stews (*wot*), which are consumed as main and side dishes along with *injera* and other breads (Wilson, 2023). In this regard, lentils constitute an important source of protein in rural areas, where the diet is mainly vegetarian (Butler & D'Andrea, 2000).

Lolium L. sp.

A total of 317 charred grains and fragments of *Lolium* have been identified at Ona Adi, constituting 3.1% of the assemblage (Fig. 3g). At Ona Adi, this plant was present in all periods, except for the PA-A transition, ranging between 9 and 35.7% (Table 2). *Lolium* often grows as a weed of cultivated plants, mainly with wheat and barley. It is associated with agricultural activity, and thus an indirect indicator of the cultivation of cereals. At Mezber, *Lolium* was recovered in all phases of the Pre-Aksumite period (Beldados et al., 2015, 2023).

Lolium thrives in a diverse range of ecological settings but exhibits a preference for well-drained soils and temperate climates, where it rapidly takes over nitrogen rich and disturbed soils with high humus content (Hannaway et al., 1999). It is commonly found in managed landscapes such as pastures, but also in fields of wheat and barley (Gill et al., 1996). According to Phillips (1995), *Lolium* sp. was introduced to the Ethiopian highlands from Southwest Asia together with wheat and barley.

Other weeds

Several other weeds were recovered from Ona Adi deposits, including *Galium spurium* L. and *Rumex* cf. *crispus* L. (Fig. 3h). *Chenopodium* cf. *album* L. Bosc ex Moq. was also identified as a weed of cultivation. Still, it is worth noting that this species is cultivated in some areas, including northern India and Nepal (see Poonia and Upadhayay 2015). In addition, there are many other wild or weedy plants ($n = 175$), which could not be reliably identified because of limitations of available reference collections. These represent 6.1% of the total assemblage. Among the identified weeds, *Galium spurium* is the most common ($n = 426$), accounting for 14.9% of the macrobotanical assemblage. In addition, *Chenopodium* cf. *album* ($n = 301$) and *Rumex* cf. *crispus* ($n = 41$) represent 10.6% and 1.4%, respectively.

Galium spurium is commonly found in cultivated and abandoned agricultural lands, especially in cereal and potato fields (Royo-Esnal et al., 2012; Sparangis et al., 2023). Similarly, *Chenopodium album* flourishes as a weed in fields and home gardens and is a pest of various cropping systems throughout the world (Tang et al., 2022). It can withstand a wide variety of environments and soils, although it does very well in fertile, well-watered soils (see Tang et al., 2022). *Rumex crispus* is a common perennial weed that grows in pastures, fields, and home gardens (see Zaller, 2004). It is a troublesome weed in both pastures and arable lands, and it can also colonise highly disturbed areas in both lowlands and high elevations up to 3500 masl (Zaller, 2004).

Phytoliths

A total of 59 single-cell morphotypes and 23 silica skeleton types were identified in the phytolith assemblage of Ona Adi. Additional taxonomic classification resulted in 19 groups of single cells and 10 groups of articulated cells (Table 3). For a detailed discussion of each morphotype and its taxonomic and anatomic association, see Ruiz-Giralt et al., (2023a, Supplementary Information: 52–114, also available at https://zenodo.org/record/7731566).

Single-Celled Phytoliths

Phytolith concentration ranged between 0.39 and 4.86 M phytoliths per gram of acid insoluble fraction of sediment (n/g AIF), averaging 1.52 ± 0.86 M n/g AIF (raw data is available at Supplementary Information 3). No correlation between phytolith concentration and number of morphotypes was found (Pearson's $r = -0.02$). This indicates that taphonomic processes did not have a significant impact on the general composition and representativeness of the phytolith assemblage. Analysis of variance by the Kruskal–Wallis H test did not show significant differences in phytolith concentration among samples according to phase or type of context. Table 3 includes the results of the analysis of the phytolith assemblage from Ona Adi by phase (the full results are included in the Supplementary Information 3). Regarding the single cells, the assemblages were rather homogeneous. Phytoliths with taxonomic value represented ca. 85% of the assemblage, with minor differences between phases as nondiagnostic morphotypes ranging from 14.4 to 17.1%. Among the rest of the assemblage, morphotypes associated with indeterminate herbaceous plants (Poaceae/Cyperaceae and Poaceae) were the most common, representing between 56 and 60% in all occupational phases. Around 22 to 24% of each phase was comprised of grass phytoliths: Panicoideae and Chloridoideae grass subfamilies represented 18.4 to 19.1% of all phases, whereas Pooideae ranged between 3.3 and 4.8%. Phytoliths associated with other monocotyledonous plant clades (including Arecaceae, Commelinaceae, Cyperaceae, and Zingiberales) encompassed between 0.9 and 2.1% of the assemblage, whereas dicotyledonous phytoliths represented 1.38 to 2.2%.

Silica skeletons

A total of 144 silica skeletons were recorded in Ona Adi deposits. The full results are presented in the Supplementary Information 4. Taxonomic identifications were proposed for all but 8.3% (*n* = 12) due to preservation issues. The average number of cells per silica skeleton was 4.9 ± 3.3, with minor differences between phases (range = 4.2 ± 3.5 to 5.3 ± 4.8). Silica skeletons from herbaceous plants dominated (90.8%, *n* = 118), whereas palms and dicotyledonous multicells encompassed 9.2% (*n* = 12) of the assemblage. The only secure Arecaceae silica skeleton was documented in a Late Aksumite context (sample C1.2.5#125), even though two other multi-cells possibly related to palms were identified in samples from Square D1 Locus 14 Pail 25 Serial #1135 and D1 Locus10 Pail 17 Serial #843 associated with PA-A transition and Early Aksumite materials, respectively. Regarding dicotyledon phytoliths, phases ranged between 3.4 and 13%, with the highest presence associated with samples from Middle Aksumite contexts (*n* = 3) and the lowest with Late Aksumite deposits (*n* = 2).

Among herbaceous plants, undifferentiated Poaceae/Cyperaceae (63.8%) was the most common type – as articulated BULLIFORMS (*n* = 50, Fig. 4a) and articulated ELONGATES ENTIRE (*n* = 23, Fig. 4b) were the most common silica skeleton types—followed by undifferentiated Poaceae (9.2%)—which mainly included silica skeletons exclusively formed by ELONGATES DENTATE (*n* = 6) and ELONGATES DENDRITIC (*n* = 6). Silica skeletons containing ELONGATES DENDRITIC with PAPILLATE(*n* = 7) and interpreted as Poaceae cf. Pooideae (5.4%) were recorded in all phases from the site except for the Late Pre-Aksumite occupation of Ona Adi. Finally, the sum of the Panicoideae types (a subfamily within Poaceae) represented the remaining 12.3% of the assemblage. These include multi-cells with ELONGATES SINUATE wavy (*n* = 2, Fig. 4d) and ELONGATES SINUATE INTERDIGITATE (*n* = 16, Fig. 4e, f, g). The highest presence of Panicoideae multi-cell was documented during the Late Pre-Aksumite occupation of the site, where 20% (*n* = 3) of the skeletons were identified as ELONGATES SINUATE INTERDIGITATE Ω-shaped (Fig. 4g) and classified as Paniceae. One ELONGATES SINUATE INTERDIGITATE Λ-shaped (Fig. 4e) interpreted as Panicoideae cf. *Setaria* was also documented from contexts associated with this phase, specifically from Square D2 Locus 26 Pail 57 Serial#1187. The subsequent PA-A transition, Early Aksumite, and Middle Aksumite phases showed lower percentages of Panicoideae grasses, ranging from 7.1 to 9.5%. Besides the skeletons associated with the Paniceae tribe, one ELONGATES SINUATE wavy multi-cell (Fig. 4d), identified as Panicoideae cf. Andropogoneae, was recorded during the PA-A transition (D2.25.56#1499) and one Panicoideae cf. *Setaria* was identified among Middle Aksumite samples (D2.8.19#1325). Lastly, the Late Aksumite phase showed 11.9% of Panicoideae morphotypes. In this case, the Andropogoneae (*n* = 1), Paniceae (*n* = 3) and cf. *Setaria* (*n* = 1) were accompanied by 2 ELONGATES SINUATE INTERDIGITATE cf. β-shaped (Fig. 4f) which were identified as Panicoideae cf. *Echinochloa*.

Discussion

Pre-Aksumite Agriculture at Ona Adi (ca. 750–1 BCE)

During the early-1st millennium BCE, the highlands of the northern Horn witnessed the proliferation of sedentary agricultural settlements associated with the Early Pre-Aksumite phase identified at Mezber (see D'Andrea et al., 2023). This process is well attested in Gulo Makeda (D'Andrea et al., 2008b, 2023; Harrower & D'Andrea, 2014; Harrower et al., 2022), where it prompted the establishment of several sites, including Ona Adi. According to the macrobotanical assemblage, the agricultural economy associated with the Pre-Aksumite occupations of Ona Adi (ca. 750 BCE–1 CE) was based

Table 3 Results of the phytolith analysis from Ona Adi by phase. *PA* Pre-Aksumite, *A* Aksumite, *PA-A T* Pre-Aksumite to Aksumite transition

Ona Adi		Single cells (in percentage)									
Period	***n* samples**	**Indet. herb**		C_4							C_3
		Poaceae/Cyperaceae	Poaceae	Andropogoneae	cf. Aristidoideae	Panicoideae/Chloridoideae	cf. Panicoideae/Chloridoideae	Panicoideae	Chloridoideae	cf. Chloridoideae	Pooideae
Late PA	3	30.6	27.4	0.1	0	9.1	0.9	0.6	8.1	0.3	3.4
PA-AT	10	24.6	31.4	0.04	0.04	7.2	1.3	0.2	10.2	0.2	4.8
Early A	11	24.7	35.1	0.03	0.03	8	1.2	0.1	9.4	0.1	3.3
Middle A	8	29.3	30.4	0	0	9.5	1.1	0.2	7.1	0.4	3.6
Late A	15	30.5	27.2	0	0	10.3	0.5	0.1	7.8	0.2	4.1
Total OA	**47**	**27.7**	**30.5**	**0.02**	**0.02**	**8.9**	**0.9**	**0.2**	**8.6**	**0.2**	**3.9**

Ona Adi	Single cells (in percentage)									Silica skeletons (in absolute counts)	
Period	**Other monocots**							Dicotyledonous	Non-diagnostic	**Skeletons total**	**Avg. cell # per skeleton**
	Arecaceae	Zingiberales	cf. Zingiberales	Cyanotis sp.	Commelina sp.	Commelinaceae	Cyperaceae				
Late PA	0.3	0.5	0	0.1	0	0	0	1.5	17.2	16	5.3 ± 4.8
PA-AT	0.3	1.4	0.2	0	0.2	0	0	2.2	15.7	22	4.8 ± 2.8
Early A	0.3	1.7	0	0.03	0	0	0	1.7	14.4	16	4.2 ± 3.5
Middle A	0.4	1	0	0	0.3	0.05	0.05	1.4	15	25	4.7 ± 3.6
Late A	0.2	0.6	0.03	0.03	0.1	0	0	1.8	16.7	65	5 ± 3
Total OA	**0.3**	**1.1**	**0.04**	**0.02**	**0.1**	**0.01**	**0.01**	**1.8**	**15.7**	**144**	**4.9 ± 3.3**

Ona Adi	Silica skeletons (in absolute counts)										
Period	**Indet. herb**		C_4				C_3	**OM**	Dicotyledonous	Non-diagnostic	Undetermined
	Poaceae/Cyperaceae	Poaceae	Panicoideae—Andropogoneae	Panicoideae—Paniceae	Panicoideae cf. *Echinochloa*	Panicoideae cf. *Setaria*	Poaceae cf. Pooideae	Arecaceae			
Late PA	4	5	0	3	0	1	0	0	1	1	1
PA-AT	11	3	1	1	0	0	2	1	2	0	1
Early A	9	0	0	1	0	0	1	1	1	1	2
Middle A	15	1	0	1	0	1	2	0	3	0	2
Late A	44	3	1	3	2	1	2	1	2	0	6
Total OA	**83**	**13**	**2**	**9**	**2**	**3**	**7**	**3**	**9**	**2**	**12**

on the cultivation of wheat, barley, and lentil. These crops appear to have dominated the economy of Mezber and most other Pre-Aksumite sites throughout the Ethiopian highlands (e.g., Beldados et al., 2023; Boardman, 2000; D'Andrea, 2008; D'Andrea et al., 2008a, 2023; Harrower et al., 2019). The presence of *Lolium* sp. remains further reinforces this idea, as it is a weed of the cultivation of these Southwest Asian crops, thought to have been introduced from Southwest Asia (Phillips, 1995). By contrast, the phytolith record indicates a completely different situation, with local grasses from the Chloridoideae and Panicoideae subfamilies representing approximately 20% of the assemblage, while Pooideae cereals only account for about 3.5%. It is interesting to note that isotopic analysis of one individual from the site of Etchmare East, located very close to Ona Adi, indicated a strongly vegetarian diet composed of 20% C4 plants (D'Andrea et al., 2011a, 2011b). Similar proportions were identified in the microbotanical residues recovered from grinding stones at Ona Adi (Ruiz-Giralt et al., 2023a). However, this should not be interpreted as the phytolith record not showing evidence of wheat and barley exploitation. Instead, it is very likely that some of the indeterminate Poaceae and Poaceae/Cyperaceae types comprising around 60% of the Ona Adi assemblage are related to Pooideae grasses. For example, phytolith morphotypes such as ELONGATE DENDRITIC, RONDEL, and TRAPEZOID have been interpreted as Pooideae until very recently (e.g., Barboni et al., 1999, 2007; Fredlund & Tieszen, 1994; Twiss et al., 1969; see Neumann et al., 2019 for further details). However, recent plant phytolith surveys of eastern African grasses have revealed a remarkable degree of redundancy of these phytolith morphotypes among wild African plants from other subfamilies, thereby significantly limiting our ability to identify Pooideae grasses in the microbotanical record (e.g., Barboni & Bremond, 2009; Novello & Barboni, 2015; Radomski & Neumann, 2011). This is further supported by the results of the silica skeletons, where the difference between Pooideae ($n = 7$) and Panicoideae ($n = 16$) subfamilies is not as marked as in the single-cells assemblage. Altogether, it is evident that both proxies need to be applied in combination to obtain a comprehensive understanding of agricultural practices at Ona Adi.

The soil phytolith assemblage at Ona Adi is dominated by local Chloridoideae and Panicoideae grasses despite their general absence in the macrobotanical record. A similar pattern was recently observed at Mezber (Beldados et al., 2023; Ruiz-Giralt et al., 2023a, 2023b). The importance of African crops in the economy of Pre-Aksumite Ona Adi is further reflected by a significant quantity of noog remains (*Guizotia abyssinica* (L. f.) Cass), including five cypselae recorded in a context associated with the PA-A transition (ca. 400 BCE–CE 1). Noog is an oil plant indigenous to the highlands of the northern Horn of Africa, where it is thought to have been domesticated (see Daniel & Beldados, 2018; Fuller & Hildebrand, 2013). It is believed to have evolved from the wild progenitor, *Guizotia scabra* (Vis. Chiov.), locally known as *mech* (Daniel & Beldados, 2018). The use of noog was identified in Tigrai during the Aksumite period by Boardman (2000) at Aksum. However, the evidence from Ona Adi represents the earliest available evidence for the use of this plant, demonstrating that it was already domesticated by the end of the 1st millennium BCE. This, in combination with the predominance of Panicoideae and Chloridoideae plants in the microbotanical record, as well as the presence of finger millet and possible t'ef macrobotanical remains in later deposits, shows that Ona Adi inhabitants intensively used indigenous African plants, whose exploitation was combined with the cultivation of exogenous crops from Southwest Asia.

The presence of phytoliths associated with the Panicoideae and Andropogoneae clades at Ona Adi since the Late Pre-Aksumite phase raises the question about the possibility of sorghum exploitation in either a wild, semi-domestic or fully domesticated state in the region as early as the mid-1st millennium BCE. The domestication process of sorghum has been a source of debate for decades (Doggett, 1965, 1991; Fuller & Hildebrand, 2013; Fuller & Stevens, 2018; Harlan, 1971; Harlan & Stemler, 1976; Vavilov, 1951; Venkateswaran et al., 2019; Winchell et al., 2018), but recent studies have built some agreement around eastern Sudan as the domestication locale of sorghum (see Barron et al., 2020; Beldados & Constantini, 2011; Beldados et al., 2018; Winchell et al., 2017). Regarding its introduction to the highlands of the northern Horn of Africa, the timing is still unclear: whereas historical linguistics studies have suggested that sorghum arrived around ca. 3500 BCE from the Sudanese lowlands (Ehret, 2011, 2014), direct archaeological evidence of this process has not yet been recovered. In this regard, recent charring experiments have shown that both wild and domestic sorghum grains cannot survive temperatures above 300 °C and 300/350 °C respectively, indicating that they are less tolerant of high temperatures than wheat and barley grains (Beldados et al., 2023; Varalli et al. 2023). The available evidence suggests that Andropogoneae grasses (of which sorghum is a member) were being systematically processed at Mezber, a rural Pre-Aksumite site in Gulo Makeda, since the mid-2nd millennium BCE (see Ruiz-Giralt et al., 2023a). Similarly, Ruiz-Giralt et al. (2023a) show that starch grains from Andropogoneae have been consistently recorded from grinding stones at Ona Adi throughout the entire occupational sequence of the site.

The location of Gulo Makeda at a crossroads between Red Sea ports and the northern highlands favored the movement of goods and peoples, thereby exposing local communities to a diverse range of agricultural traditions and resources. These may have included Southwest Asian crops, which appear fully integrated into the highland agricultural system by the mid-2nd millennium BCE (Beldados et al., 2023), and it could have also prompted the introduction of sorghum exploitation (Ruiz-Giralt et al., 2023a). Nevertheless, the evidence from Ona Adi suggests that the adoption of exogenous crops did not result in the abandonment of the use of indigenous plants. Recent studies at the site of Mezber also support this claim (Beldados et al., 2023; Ruiz-Giralt et al., 2023a). The data from Ona Adi demonstrate that the exploitation of local plants, both wild and domesticated, was not a unique characteristic of mobile agro-pastoral groups that occupied the region during the 2nd millennium BCE hence supporting the hypothesis introduced in recent studies by the authors (Beldados et al., 2023; Ruiz-Giralt et al., 2023a). Instead, these mixed economies became long-term subsistence strategies, which continued after agricultural intensification associated with the expansion of sedentary settlements after the eighth century BCE, leading to the eventual domestication of some local species such as noog, t'ef and possibly finger millet at some point during the late-1st millennium BCE to the early-1st millennium CE. 6.2. Agricultural systems at Ona Adi during the Aksumite Period (ca. 1–700 CE).

Agricultural systems at Ona Adi during the Aksumite Period (ca. 1 - 700 CE)

The transition to the Aksumite period followed by the expansion of the Kingdom of Aksum throughout the highlands of the northern Horn did not produce abrupt alterations in the agricultural economy of Ona Adi. Despite becoming a regional center of settlement during these centuries, Ona Adi continued to possess a diverse agricultural package that included the same Southwest Asian products as well as a number of African crops, including noog, t'ef, finger millet and possibly sorghum. Similar results were obtained from the analysis of microbotanical residues on grinding stones by Ruiz-Giralt et al. (2023a), which also noted the presence of starchy plants, including members of the Brassicaceae, Zingiberaceae, and Dioscoreacae families. It does appear that the Pre-Aksumite emphasis on cereal agriculture may have been somewhat reduced during the Aksumite period, when a diverse range of pulses were adopted, including chickpeas (*Cicer arietinum* L), horse bean (*Vicia faba* L.), grass pea (*Lathyrus sativus*), and pea (*Pisum sativum* L.); as well as other important economic crops such as cress (*Lepidium sativum* L.), gourds (Cucurbitaceae Juss.), cotton (*Gossypium* L. sp.) and grapes (*Vitis* L. sp.), which have been identified in a number of localities around Aksum (Boardman, 2000; D'Andrea, 2008). By contrast, the archaeobotanical evidence from Ona Adi suggests a significant degree of continuity between Pre-Aksumite and Aksumite cultural complexes, with a continued focus on domesticated cereals and wild grass cultivation, the most significant difference being the increased importance of wheat in Aksumite times.

Emmer and free-threshing wheat are known to have become major staple crops throughout the northern Horn during the 1st millennium CE (Boardman, 2000; D'Andrea, 2008; Schmidt, 2009). The depiction of emmer wheat on Aksumite coinage encircling the heads of kings indicates that the importance of wheat during the Kingdom of Aksum was not only economic but also symbolic (D'Andrea & Haile, 2002; Munro-Hay, 1991; Schmidt, 2009). At Ona Adi, a significant increase in the presence of wheat grains is recorded during the Middle Aksumite phase, when they represent over 60% of the macrobotanical assemblage and more than 85% of the domesticated specimens (Fig. 5). During the Late Aksumite occupation of the site, wheat continues to be the dominant cereal crop, although by this time a significant number of noog remains have also been identified. By contrast, no evidence of this process is recorded in the soil phytolith assemblage, which shows lower values of Pooideae phytoliths during the middle phase (3.6%) than during the PA-A transition phase (4.8%). It is noteworthy that a second evaluation of the phytolith results from the grinding stones analyzed by Ruiz-Giralt et al. (2023a) have revealed a significant pattern that could reflect the same process identified in the macrobotanical record: when the morphotypes traditionally associated with Pooideae grasses (i.e., ELONGATE DENDRITIC, RONDEL, and TRAPEZOID) are interpreted as such, a gradual increase is recorded from the Pre-Aksumite occupations of Ona Adi (ca. 25%) to the Aksumite phases of the sequence, increasing by around 5% during the early and middle phases (to ca. 30%) and by an extra 10% during the Late Aksumite phase (ca. 40%). It is worth noting that this pattern is not reproduced in the soil phytolith assemblage, which records a ca. 5% increase from the Late Pre-Aksumite phase (15.6%) to the PA-A transition (21.2%), but it remains constant ranging from 19 to 21.5% during the Aksumite occupations of the site. Taken together, the archaeobotanical evidence from Ona Adi supports previous claims about the increased importance of wheat in the economy of the Aksumite Kingdom (Boardman, 2000; D'Andrea, 2008; Schmidt, 2009).

Whether this rise in the importance of wheat in the Kingdom of Aksum preceded or followed the period of demographic growth documented by Harrower et al. (2022) has yet to be determined. At Ona Adi, clear evidence of this process is recorded during the Middle Aksumite phase, thereby suggesting that the population increase recorded at Gulo Makeda predated the Aksumite focus on wheat cultivation. This would indicate that the transition from the Pre-Aksumite to the Aksumite period did not produce this shift in agricultural strategies. Instead, the production and consumption of wheat increased later, perhaps fostered by the Aksumite state in an attempt to promote a process of agricultural intensification that increased the productivity of preexisting local economies. The promotion of wheat agriculture as a way to increase agricultural productivity has also been described for other contemporary ancient states such as the Han empire in eastern Asia, ca. 200 BCE to 200 CE (Li & Zhuang, 2022), and the Byzantine empire around the Mediterranean, ca. 300 to 600 CE (Farahani, 2018). In this sense, historical sources indicate that the Aksumite Kingdom had some degree of control over agricultural production as demonstrated by its capacity to gather resources and issue food rations on a substantial scale when the socio-political situation required it (Munro-Hay, 1991). For example, the Safra Inscription appears to deal with extraordinary food assignments, including meat, bread, and beer, possibly related with the presence of King Ezana (ca. 320–360 CE) in the area (see Drewes, 1962: 30; cited in Munro-Hay, 1991: 141). Similarly, in the Geza Agmai inscription about the Beja war, King Ezana stated:

> Since the people of the Beja rose up, we sent our brothers Saiazana and Adefan to fight them. When these had taken arms against the enemy, they made them submit and they brought them to us with their dependents (…). My brothers gave them meat and wheat to eat, and beer, wine and water to drink, all to their satisfaction whatever their number. There were six chiefs with their peoples, to the number of 4,400 and they received each day 22,000 loaves of wheat and wine for four months, until my brothers had brought them to me. (…) and we commanded again that they be given supplies; and we accorded to each chief 25,140 head of cattle. (Bernand, 1982: 107; cited in Munro-Hay, 1991: 189).

In addition to the documented ability of Aksumite kings to collect and distribute agricultural resources, some scholars have hypothesised that the Aksumite state had control over large-scale irrigation systems that enabled the intensive cultivation needed to sustain an increasing population (Kobishchanov, 1979; Michels, 2005). However, recent studies have highlighted the absence of archaeological evidence of large irrigation structures in the northern Horn (D'Andrea 2008b; Harrower et al., 2020; Sulas et al., 2009; Sulas, 2014, 2018). Moreover, ethnoarchaeological models and phytolith data point to an agricultural landscape dominated by rainfed agriculture during the Aksumite period (Ruiz-Giralt et al., 2023b). It has been argued that rainfed agriculture (perhaps complemented with some small-scale irrigation similar to what can be observed today (see Biagetti et al., 2022; Harrower et al., 2020), could have been enough to sustain the growing Aksumite population, proving itself to be a sustainable and flexible strategy able to support the emergence of an urban society without the need of state-level control of water resources (see Harrower et al., 2020; Ruiz-Giralt et al., 2023b; Sulas et al., 2009). In this regard, authors such as Sulas et al., (2009; Sulas, 2014) have proposed that agricultural activities during the Aksumite period were not controlled by the state but were instead highly dependent on the bimodal precipitation regime that characterises the region (see Sulas et al., 2009; Sulas, 2014 for further details). According to McCann (2001) such a marked seasonality with long dry seasons and short rainy seasons would have enabled people to participate in other activities during the times when they are not working in fields. These activities could have been organised by the Aksumite state (McCann, 2001), following an organisation of labor similar to the *corvée* systems that operated in other ancient states such as Pharaonic Egypt (Allen, 1997; Brown, 1994), Mesopotamia (Steinkeller 2013), the Hittites (Bilgin, 2018), the Inca (Garrido & Salazar, 2017), the Qing Dynasty (Dai, 2001), and the Roman Empire (see Verboven & Laes, 2016 and references therein). It is noteworthy that a similar system of compulsory work for the state is known to have been used by the Ethiopian Empire (1270–1974 CE) (see Crummey, 1980; Griaule, 1931; Kropp, 1988; Zewde, 2023). Another possibility is that Aksumite farmers were involved in the cultivation of state-owned land, as occurred in medieval Ethiopia (see Wion, 2020: 408), where they may have cultivated wheat by request of Aksumite institutions.

The increased importance of wheat during the Aksumite period at Ona Adi does not imply an abandonment of the use of indigenous African grasses, either wild or domesticated as shown by the microbotanical record. During the Aksumite occupations of Ona Adi, the phytolith assemblage was composed of ca. 20% of Chloridoideae and Panicoideae phytoliths, which were likely derived from a combination of both wild and domesticated African grasses. This is supported by two lines of evidence. First, the macrobotanical evidence of domesticated t'ef and finger millet during the Early and Late Aksumite phases, respectively, along with the results of the starch analysis by Ruiz-Giralt et al. (2023a) indicates that these grasses were likely being consumed at Ona Adi since the Pre-Aksumite occupation of the site. Secondly, the recording of a number of silica skeletons related to wild millets points towards a mixed economy that included both domestic and wild plants, in a similar fashion to what was identified at the Pre-Aksumite site Mezber during the 2nd millennium BCE (Ruiz-Giralt et al., 2023a). This indicates that despite the socio-political changes derived from the emergence of the Aksumite Kingdom, local agricultural economies show a significant degree of continuity with respect to the Pre-Aksumite period. Indeed, the development of state-level institutions does not conflict with a household-based economy based on the management of local resources as noted by Sulas et al. (2009).

The archaeobotanical data from Ona Adi indicate that there could have been a state-fostered process of agricultural intensification based on the promotion of wheat agriculture. This increase in wheat production appears to have been an economic choice rather than the result of changing environmental conditions, as these are known to have remained relatively stable in the region (see Blond et al., 2021; French et al., 2017; Ruiz-Giralt et al., 2021; Terwilliger et al., 2011, 2013). No abrupt climatic changes have affected the region since ca. 2200 BCE, when current environmental conditions were established (e.g., Tierney & de Menocal, 2013). If we consider recent research which has shown that long-term sustainable agriculture using traditional agricultural techniques in the northern Horn of Africa would require extensive cultivation regimes based on the use of long periods of fallow (Ruiz-Giralt et al., 2023b), it can be hypothesised that the intensification of agricultural activities during the Aksumite period initiated a process of soil impoverishment that could have provoked a gradual decline in agricultural productivity. This could have triggered an internal economic crisis which, along with a series of internal and external socio-political events such as the Beja invasion or the loss of the control over Red Sea trade networks (see Fattovich, 2010; Phillipson, 2012), led to the decline of Aksumite institutions as a result of elites losing their economic power. A similar theory was proposed by Butzer (1981), who argued that the fall of the Kingdom of Aksum in the early ninth century BCE was primarily driven by agricultural collapse resulting from increased anthropic land pressure. However, the archaeobotanical record from the Post Aksumite phase of Ona Adi does not demonstrate significant differences with respect to earlier occupations of the site, thereby suggesting that agricultural economies were mostly maintained at the local level despite the fall of the Aksumite Kingdom. It is more plausible that economic collapse was limited to the Aksum area, where a significant decrease in population and wealth has been recorded (e.g., Michels, 2005; Munro-Hay, 1989; see Phillipson, 2012: 209–211 for a detailed review). Indeed, a number of studies have shown that rural settlements persisted in relatively significant numbers throughout the countryside, not only in the hinterlands of Aksum throughout Central Tigrai, but also in other areas of the kingdom such as Eastern Tigrai (e.g., D'Andrea 2008b; Harrower & D'Andrea, 2014; Harrower et al., 2022; Sernicola, 2008, 2017; Sernicola & Sulas, 2012). This is remarkable as it demonstrates the resilience of Aksumite agricultural systems at the local level, demonstrating a significant degree of continuity despite cultural changes such as the Pre-Aksumite to Aksumite transition, or the influence of socio-political actors such as the rise and fall of the Kingdom of Aksum.

Concluding Remarks

The archaeobotanical assemblage from Ona Adi fully supports previous findings of an agricultural economy based on a diverse range of plant resources, including both wild and domesticated taxa, since the Middle/Late Pre-Aksumite occupation of the site, ca. 750/600 BCE (e.g., Beldados et al., 2023; Ruiz-Giralt et al., 2023a, 2023b). At Ona Adi, these include exogenous crops such as wheat, barley, lentil and flax, and also indigenous species such as noog, finger millet and possibly t'ef. The noog remains identified at Ona Adi during the Pre-Aksumite to Aksumite transition phase (ca. 400–1 BCE) represent the earliest evidence of the use of this crop recorded to date. It is important to point out that a more complete picture of Ona Adi agricultural economy was possible only through the investigation of both macro- and microbotanical data: neither of these remains on their own reflected the crop diversity present at the site. Our results also indicate that the emergence of the Aksumite Kingdom did not trigger an abrupt change in the local agricultural economy of the site, which continued into the early 1st millennium CE without major changes. Still, an increase in the use of wheat (likely emmer) is recorded throughout the Aksumite period, especially in the carpological record during the Middle Aksumite occupation of the site, which is hypothesised to be the result of the promotion by the central powers of the Aksumite state. Though less clear, this is also reflected in the phytolith record of the site, especially in the microbotanical assemblage recovered from the grinding stones (see Ruiz-Giralt et al., 2023a). Further systematic archaeobotanical investigations in the region, integrating both macro- and microbotanical remains, are necessary to confirm this hypothesis. In any case, the general homogeneity of the phytolith assemblage in relation to the previous Pre-Aksumite occupation at Ona Adi, but also other sites such as Mezber (ca. 1600 BCE–25 CE, see Beldados et al., 2023), indicates that agricultural economies were mostly maintained at the local level despite the increased presence of Southwest Asian crops. This model has parallels in wider northeastern Africa (e.g., Barakat et al., 1999; Beldados et al., 2018; Beldados, 2019; Harlan, 1989; Le Moyne et al., 2023; Lucarini & Radini, 2020; Lucarini et al., 2016; Madella et al., 2014; Out et al., 2016; Winchell et al., 2017), but also in other areas of the African continent (Cagnato et al., 2022; Goldstein et al., 2021), where similar systems are known to have been in place for hundreds (or thousands) of years hence demonstrating their adaptability and resilience. Indeed, the influence of these ancient food systems can still be observed in modern-day Tigrai (see Biagetti et al., 2022; Butler & D'Andrea, 2000; D'Andrea & Wadge, 2011; Lyons & D'Andrea, 2003; Lyons, 2007; Nixon-Darcus, 2014, 2022; Nixon-Darcus & D'Andrea, 2017; Nixon-Darcus & Meresa, 2020).

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Data Availability The authors confirm that the data supporting the findings of this study are available within the article and its supplementary materials. Supplementary data is also available in an open repository at: https://doi.org/10.5281/zenodo.8340658.

Declarations

Competing Interests The authors declare no competing interests.

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